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Space-weather – causes, consequences and predictions

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Abstract : Space-weather defines variation in the plasma speed and density, solar magnetic field and radiation density in the near Earth-space environment and consequences of those variations. It is scientifically interesting and challenging research field that has significant economic importance all over the world. Adverse changes in the near Earth-space environment can diminish the performance and reliability of both spacecraft and ground-based systems. In the present paper, we have described the causes and effects of space weather Some means for space-weather predictions are also suggested

Keywords Space-weather, coronal mass ejection, geomagnetic activity

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1. Introduction

Dynamic, highly variable conditions in the geo-space environment including those on the Sun, in the interplanetary medium, and in the ionosphere-magnetosphere system may be called as space-weather [1] as it has important consequences in almost all the phenomena studied in space physics. Geomagnetic activity is the main factor controlling the space weather. In addition to the geomagnetic activity, changes in the atmosphere, or even comets and man made debris in space can also be of importance. The most obvious effects of the geomagnetic activity (usually coronal mass ejection (CME) driven storms) is the buildup of enhanced ionospheric current system within the equator-ward moving auroral oval. As a consequence, current surges can be induced in power lines, causing flickering lights and blackouts resulting millions of dollars worth of damage. Apart from these, telecommunication cables and even petroleum pipelines are also affected. The other serious consequence of bad space-weather is the possibility of damage to Earth orbiting satellites. Both storm-time medium energy CME particles and flare related high-energy solar (cosmic ray) particles are responsible for the problem. The damages can be a single instant breakdown of some internal electronic component or increased deterioration of satellites during repeated passes through the radiation belts and hitting manmade debris or comets. Geomagnetic activity is also an important source of enhanced Joule heating and it is possible that flare related X-ray radiation could do some additional heating too.

In this paper, we discuss briefly the major factors responsible for space-weather. The emphasis will be on solar wind and magnetospheric disturbances that are responsible for adverse effects of space-weather and cause problems for spacecraft or ground stations. A particular important aspect of the solar terrestrial environment is the degree to which it produces operational anomalies. The occurrence of large disturbances on the Sun's surface have long been known to be followed after a few hours to a few days by significant geomagnetic disturbances. The nature of the terrestrial effects can include large magnetic storms, ionospheric disruptions, and intense surface events. We now know that coronal disturbances often accelerate very energetic particles and also often give rise to strong travelling shock waves in the interplanetary medium. Given a proper interplanetary magnetic field (IMF) connection between the disturbance site on the Sun and the Earth, very energetic solar protons can begin reaching the terrestrial environs within tens of minutes and may peak in a matter of hours. At Earth, these very energetic protons appear to have

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ready access to the polar cap regions and the outer magnetosphere [2]. Within the last few years, we have come to recognize several primary features of the space environment that produce these deleterious effects.

2. Causes of space weather

In order to protect systems and people that might be at risk from space-weather effects, it is essential to understand the processes taking place throughout the region spanning from the Sun to the Earth. The space-weather has its origin in solar activity. Sudden ejection of plasma and magnetic field structures from the Sun's atmosphere called coronal mass ejection together with sudden burst of radiation termed solar flares influence the Earth's environment to produce space weather effects. In addition, galactic cosmic rays, originating from far beyond the solar system also cause a type of space weather effect and so their influence on the Earth also needs to be understood for predictions of space-weather [3].

2.1 Solar activity :

Solar activity includes phenomena related with solar flares, solar energetic particle events, coronal mass ejection (CME), solar wind and their recurrence in time and space. A solar flare is a sudden and explosive release of energy in the solar atmosphere. This energy is released as particle acceleration, plasma heating and dramatically enhanced radiation. They may last for a minute to several hours. The frequency of flares coincides with the Sun's eleven-year cycle. When the solar cycle is at a minimum, active regions are small and rare and few solar flares are detected. Solar energetic particle events occur sporadically and they are typically associated with events taking place on the Sun, such as flares and coronal mass ejection. There is, however, currently controversy as to whether particle acceleration takes place in the flare itself or whether the particles are accelerated by associated CMEs [4] which carry large amount of plasma and magnetic fields in the heliosphere and is readily detected by remote sensing and *in-situ* spacecraft observations.

2.1.1 Coronal mass ejections (CMEs) :

The white light images of CMEs contain a bright leading loop-like structure followed by a dark cavity and a bright core of denser material. Figure [1] shows the eruption of a prevalent prominence, its overlying coronal cavity and the ambient corona. Recent studies confirm that CMEs arise from large scale, closed structures, most of which (~75%) are pre-existing coronal streamers [5, 6]. The temporal and latitudinal distributions of CMEs are similar to those of streamers and prominences, being confined to low latitudes about the current sheet near solar cycle minimum and becoming distributed over all latitudes near maximum [5]. This evolution differs from active regions, flares or sunspots. Many energetic CMEs seem to be disrupted pre-existing streamer, which increases in brightness and size for days before erupting as a CME. After the streamer and CME disappear, a thin ray appears in the location of the streamer which may be a current sheet arising from a nearly reformed streamer. Feynmann and Martin [7] showed that major erupting filaments are strongly associated with emerging magnetic flux oriented so as to favour reconnection of field lines. Since filament eruptions are associated with CMEs and streamers, it is argued that the emerging flux could destabilize the streamers. CME is also associated with large scale evolving pattern of existing surface flux which may be delineated by polarity inversion lines [6]. Numerical simulations show that slow, intermediate and fast mode shocks should form ahead of CMEs with speeds of 200-300, 300-900 and > 900 km/s, respectively. The existence of fast mode shocks in the corona is strongly supported by the observation of rapidly drifting radio bursts and their association with fast (> 400 km) CMEs [8].

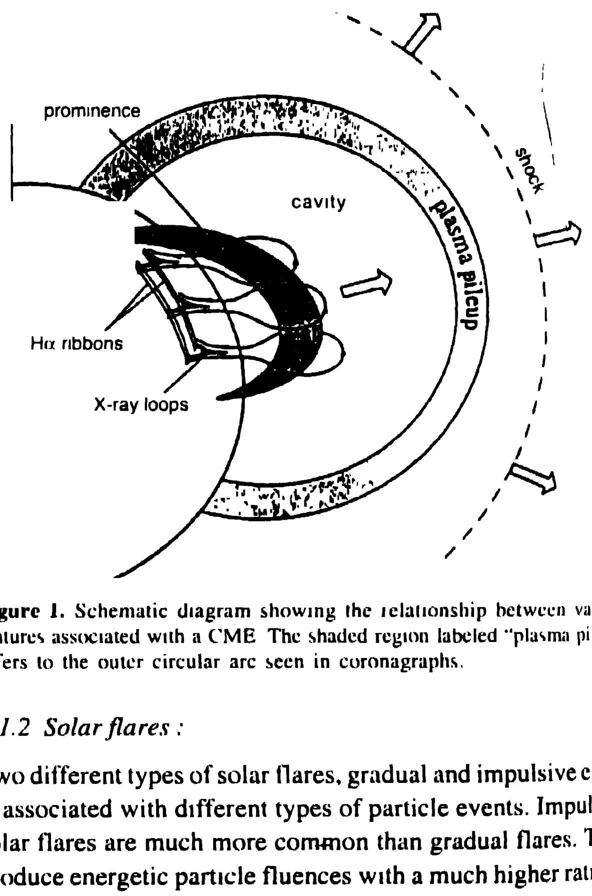

Figure 1. Schematic diagram showing the relationship between various features associated with a CME. The shaded region labeled "plasma pileup" refers to the outer circular arc seen in coronagraphs.

2.1.2 Solar flares :

Two different types of solar flares, gradual and impulsive event is associated with different types of particle events. Impulsive solar flares are much more common than gradual flares. They produce energetic particle fluences with a much higher ratio of heavy ions to protons. Studies of the composition indicate that the ions are from regions of the corona having electron temperatures of 3-5 million-degree Kelvin [9]. If these events had large proton fluences, they would be very important for space weather. However, they are generally dominated by electron fluxes and have small proton and ion fluxes [9]. Neither the positively charged particles nor the electrons in the vicinity of Earth present any significant space weather hazard. Gradual flares, often called long duration events, are strongly associated with CMEs and tend to be the events with the largest proton fluences and the highest proton peak fluxes. It is widely believed that these particles are accelerated by shocks produced by CMEs that are supersonic with respect to plasma in the corona and near – Sun solar wind [10]. If the CME velocity is super –Alfvénic with respect to the ambient solar wind, a shock will form, and particles will be accelerated. For a CME propagating into an ambient solar wind with a typical velocity of about 400 km/s, a velocity of about 700 km/s is required for the CME to be super-Alfvénic near the Sun. Occasionally, CMEs contain magnetic clouds in which the internal pressure due to particles and particularly due to the strong magnetic fields, is larger than the pressure of the ambient solar wind. Such clouds expand as they move from the Sun to Earth, and if that expansion is fast enough, both forward and reverse shock will form [11]. Figure [1] shows forward shock propagation, plasma pile up *etc*. These shocks can also accelerate particles, although they are much less common than shocks due to high speed CMEs. Recent studies confirm that CMEs arise from large scale closed structure, most of which (~75%) are pre-existing coronal streamer [5]. Further, it has been shown that major erupting filaments are strongly associated with emerging magnetic flux oriented so as to favour reconnection of field lines.

2.2 Geomagnetic activities: storms, substorms :

The CMEs colliding with the Earth, excites geomagnetic storm which is characterized by the increased convection within the magnetosphere. The substorms are associated with the appearance of fluxes of high energy electrons and ions in the vicinity of geo-synchronous altitude of the night side of the Sun and are accompanied with aurora and current surges in the ionosphere. Although, the details of the processes are still a matter of intense research, there is no doubt that the magnetosphere response to the rate of magnetic reconnection at the magnetopause is governed mainly by the intensity of the southward interplanetary magnetic field alongwith its variation and solar wind velocity. Geomagnetic storms were studied for many decades before the solar wind was observed *in-situ* by space instruments. Two types of storms had been distinguished: Sudden commencement and recurrent. Sudden commencement storms are caused by the arrival of CME-driven disturbances at the magnetosphere and recurrent storms are caused by the arrival of high speed streams of solar wind from long-lived coronal holes. A sudden commencement of storm begins with a sudden increase in intensity of the magnetic field measured at the surface of Earth. In about half-the cases, there is an initial phase to the storm in which the intensity remains high for several hours and the field is only mildly disturbed [12]. The storm then enters the main phase in which the magnetic field is highly disturbed and a ring current (a major contributor to the Dst index) is formed within the magnetosphere [13]. The decay rate of the ring current is dependent on the composition and thus become a function of solar cycle and intensity of Dst (Disturbance Solar Transients). The main phase are accompanied by substorms, aurora and strong currents in the ionosphere. The main phase of the storm corresponds to the portion of the interplanetary disturbance in which the field is strongly southward. The compressed interplanetary magnetic field between the shock and the plasma front is either north or south pointing, depending on the direction of field in the ambient solar wind and how much it turns as it passes through the shock. Because the ambient solar wind can not penetrate the CMEs, it drapes around it. If the draped field is north pointing, the storm has an initial phase; if it is south pointing the main phase begins immediately. The field within the CME itself is typically very strong and often characterized by magnetic clouds in which a field undergoes a simple rotation over many hours. There is a seasonal effect in the size of geomagnetic storms. About 65% of the most disturbed ½ day periods occur near the spring or fall equinox, whereas 35% occur near the solstices [14]. This dominance of the equinoxes is also seen in the occurrence of great geomagnetic storms, and it has been suggested that this may be primarily due to lack of response to CMEs associated with disappearing solar filaments. These seasonal effects are usually attributed to the modulation of the southward component of the interplanetary field because of the tip of Earth's magnetic pole relative to the solar equatorial plane [15].

As discussed above, the source for high-energy particles in space are fast CMEs and when the same fast-CMEs arrive at Earth, they disturb the magnetosphere. Thus, the most important events for the evaluation of hazards both in space and within the magnetosphere are high speed CMEs, since they cause both solar energetic particles and major geomagnetic storms and aurora. However, there are important differences in timing that must be kept in mind. The fluxes of energetic particles typically increase within a few hours after the CME is initiated [16]. In contrast, the geomagnetic storm does not take place until CME disturbance itself reaches the Earth, 1 to 4 days latter. This difference in time-lag between the CME and its hazardous effects produce a fundamental difference in the problem of predicting space weather.

2.3 Radiation belts :

The magnetosphere contains particles trapped and quasi-trapped in the Earth's radiation belts. The trapped protons (L<4) in the inner zone has a maximum flux with E>10 Mev at about $2R_e$ in the Earth's equatorial plane which is fairly stable for energies greater than 200 KeV except for occasional perturbations at its outer edge due to geomagnetic storms. The origin of trapped heavy ions appear to be solar wind, ionosphere, anomalous cosmic rays and solar energetic particles events [17]. Energetic electrons are also present in the magnetosphere. Electrons in the tens to hundreds of Kev are injected into the trapping region of the inner magnetosphere during substorms and magnetospheric convection. The physical relation between substorms and changes in radiation belt is currently a subject of intense controversy [13] and out of scope of this paper. As the particles drift inwards, their energy increases because of the conservation of first adiabatic invariant. This is the source of most of the trapped relativistic electrons. There is no general agreement concerning processes that produce them, although recent studies favour production within the magnetosphere. They are important for space weather because satellite anomalies have frequently been linked to them [18].

2.4 Galactic cosmic rays :

Galactic cosmic rays are present throughout the heliosphere at all times with a flux that is almost completely isotropic but is solar cycle dependent. The solar cycle dependence is caused by the modulation of the interstellar cosmic ray particles incident on the heliopause as they propagate through the solar wind within the heliosphere [19]. Galactic cosmic rays dominate the radiation environment at energies greater than about 200 Kev unless a solar particle event is in progress. Galactic cosmic rays also contribute to trapped particle population, particularly in the inner magnetosphere (L<1,5) [20]. A second source of solar cycle variation is the anomalous component of the cosmic rays. Out side the magnetosphere, there are particles with energies of 1 to 50 MeV. They are interstellar neutral particles that have been ionized within the heliosphere and then further accelerated in the outer heliosphere. In contrast to ordinary galactic cosmic rays, they have low ionization states. The regions of the magnetosphere to which they can penetrate depend on the ionization state.

3. Effects of space-weather

The modern satellites, global communication systems, defense systems and wide variety of electronic equipments require precise knowledge of the near Earth-space environment such as solar and ionospheric conditions, magnetospheric disturbance levels, solar and galactic cosmic ray fluxes *etc.* Problems such as crew and passenger radiation risks on aircraft, communication, effects on synthetic aperture radar systems, GPS systems *etc.* may all be directly linked to the above and should be taken very seriously. The cost and insurance aspects also can be considered to look into the problem. The few major effects of space weather can be categorized as following.

3.1 Surges in power lines :

The space-weather controlling factors produce fluctuations in the ionospheric current systems which induces a flow of quasi-direct current on the surface of the Earth and into man made structures such as transmission lines, communication cables, pipelines, railway tracks *etc.* In the pipelines, the integrated effects of these currents over periods of years is to contribute to the corrosion/degradation of the pipeline materials [21]. Current surges in powerlines can produce over-voltage, resulting in the damage of costly equipments. Severe geomagnetic storms could completely shut-down the power system [22]. Induced currents have also been found responsible in causing signalling errors in high speed railway system in Europe. It may also generate false readings during geophysical prospecting and thus may affect surveys and other related work.

3.2 Biological effects :

Over the poles, the Earth's magnetic field does not adequately protect the environment from high energy particles. The particles can affect aircraft crew and passengers especially on the polar routes, and this is something that should be seriously investigated. To resolve this problem, prediction of high energy solar particle events is required. Galactic cosmic rays although do not pose any risk to aircraft crew but the effect is significant for the astronauts who are on long duration mission beyond the Earth's magnetic field.

3.3 Effects on spacecraft and aircraft electronics :

High energy charged particles typically with energies of tens of KeV, can cause surface charging of the spacecraft to a potential approximately equal to the energies of the charged particles. Absolute charging of high potentials of the order of tens of KeV of a given isolated surface is not in itself a problem, however, differential charging where a dielectric surface can become charged to tens of KeV relative to nearby surface (metals or dielectric), can produce discharges between the surfaces, giving rise to spurious electric signals and spacecraft anomalies. Electrical discharges interact with electronic memory causing permanent change in electronic memory. This could change spacecraft control command such as orientation/communication interactions and render the spacecraft useless. High energy particles may also cause materials degradation of optical fiber performance through the creation of absorption regions. This can be important in satellite system employing optical fibers because of their low power consumption.

3.4 Effects on communications :

During CMEs/intense solar wind impact, ionospheric electron density increases which severely affect high frequency communication occasionally leading to total blackouts. Further, increased electron density irregularities may change amplitude/phase of VHF and UHF signals affecting satellite communication which are important for navigation, commercial communication and defense purposes. Radar systems utilizing the ionosphere for reflections to view over the horizon may also be affected

3.5 Effects on the ionosphere/magnetosphere :

Interaction of CMEs/solar wind with the outer boundary of the magnetosphere produces changes in the ionosphere and magnetosphere. On the dayside, the basic physics underlying the processes involved in the reconnection between the IMF and the Earth's magnetic field leading to small scale structures in the cusp and development of large scale behaviour associated with magnetospheric substorms [23-26]. Apart from the unloading part of the expansion phase, flux transport events on the dayside, expansion phase onsets and intensification on the night side are to be studied and understood. Development and response of the system under extreme conditions also remains to be investigated.

4. Space-weather predictions

Space-weather predictions are involved in forecasting of time of arrival of CMEs, solar wind, cosmic ray, galactic cosmic rays at the outer boundary of the magnetosphere and its interaction with it. It depends both on the understanding of the phenomena, its consequences and the development of technological capability. Thus, the challenge of making a prediction of space weather depends strongly on how the prediction will be used. The problem is complicated by the fact that a device in space can be affected in many different ways.

The prediction of geomagnetic activity comes down to a prediction of the state of the solar wind at the magnetopause. This involves the prediction or observation of high speed CMEs headed towards the Earth and the prediction or observation of fast solar wind from quasi-stable coronal holes. Observations of events at the Sun allow a prediction with a lead-time governed by the velocity of the solar wind. At present, although observations of the solar disk permit the detection of a CME or a coronal hole, the velocity is not directly observable. Most major geomagnetic storms are caused by high velocity CMEs, particularly from near the solar central meridian. The prediction of major storms then requires the prediction of the arrival of high speed CMEs at the Earth and the prediction of the magnitude and direction of the field within them and in the post shock compressed solar wind. If the velocity of a CME launched in the direction of the Earth is known at the Sun, its arrival at the Earth can be roughly estimated. The state of the magnetosphere is traditionally described by a variety of geomagnetic indices. For example, the *Dst* (Disturbance Solar Transients) index is related to the ring current, AE (Auroral Electrojet) index is a measure of the strength of substorms. It, in turn, is made up of an AU (Auroral Upper) index and AL (Auroral Lower) index that reflect the intensity of the dawnside and duskside ionospheric currents. Mid-latitude geomagnetic disturbances are described by indices that express the range of magnetic field variation seen in three hours interval such as K_P, A_P *etc*. They are all very strongly correlated to one another. In sum, geomagnetic indices are only poor measures of the quantities of importance to most space hazards predictions. To predict magnetospheric conditions with lead-times of hours, the solar wind parameters in the upstream from the Earth must be used as input to some numerical model of the magnetospheric response. Several sophisticated models are now under active development and have had some success at reproducing major aspects of post-magnetic storms [27]. However, they are not yet ready to be used in forecasting.

The prediction of the cosmic ray fluence in space on long time scales involves identifying the phase of solar cycle during which spacecraft will be flown and whether the cycle number is even or odd. Adams *et al* [28] and Adams [29] have modelled the galactic cosmic ray environment. When a cosmic ray enters the magnetosphere, its trajectory will be highly influenced by the Earth's magnetic field and the configuration of the magnetosphere. The main field of the Earth changes relatively slowly with time, but for the accurate prediction of the paths of cosmic rays and other particles within the magnetosphere, the magnetic field model of the Earth used should be as recent as possible, probably not more than 15 years old so that the position of the South Atlantic anomaly is taken correctly [30].

5. Conclusions

In this paper, we have briefly tried to point out the factors controlling the space weather and their effects on the day-to-day life Good progress is being made in understanding, modelling and predicting hazardous effects of space environments. Several areas in which advances are required for scientific understanding of the causes of hazardous space-weather and for predicting and forecasting, have been identified.

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